

TITLE: CORNER-TURNING IN TATB

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MASTER

SUBMITTED TO: Seventh Symposium (International) on Detonation
Naval Surface Weapons Center

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CORNER-TURNING IN TATB

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Descriptions are given of two tests for measuring the tendency of a point-initiated detonation wave to diverge so as to propagate at right angles to the axis of initiation ("turn the corner"). These tests were used to study the effects of initiator diameter and of acceptor temperature and density on the corner-turning distance in self-boosted PBX-9502 (95wt% TATB/5wt% Kel-F800). Measurements were made of the radial distance at which corner-turning was achieved, and the volume of undetonated explosive was calculated. Generally, the corner-turning distances increased with increase in the density and with decreases in the initiator diameter and the temperature. Both high densities and low temperatures caused anomalous and significant changes in corner-turning radius and the volume of the dark (largely undetonated) region.

1. INTRODUCTION

When a detonation wave from a small detonator or booster enters a larger charge of explosive, the detonation wave may fail or may propagate and consume part or all of the charge. If the detonation wave diverges so that it travels at a right angle to the direction of initiation we say, for want of a better term, that it has "turned the corner."

Exploration of this process waited of necessity for the development of adequate cameras and photographic techniques. Weibull [1] used a camera with a photographic film moving at 0.1 mm/ μ s in an attempt to test "an old belief that the detonation wave must travel a certain distance from the initiating point before attaining its final speed." From observations on wave divergence in a charge of pressed TNT initiated by a small detonator, he came to the conclusion that "detonation is propagated with uniform speed in all directions from the detonator."

Shepherd [2] disagreed with these findings as not according with general experience. He showed that a low propagation rate preceding full detonation velocity was exhibited by pressed tetryl ($\rho = 1.10$ g/cm³) initiated by a number six detonator. He further surmised that there was a "real, though small" difference in the detonation rate about a small initiation source due to the short radius of the wave.

Mitchell and Paterson [3] observed that in liquid nitroglycerin, where the transparency of the explosive permitted observation of the

spread of detonation, "the initial velocity of detonation normal to the axis of the detonator was appreciably less than that along the axis." They established that much of the wave in the axial direction spread spherically, and, by assuming a constant velocity, attempted to establish the apparent center of the wave through an analysis of the breakout record.

Jones and Mitchell [4] generally agreed with Shepherd's finding that a transitory low velocity could be observed in some high explosives, particularly liquid and gelatinous explosives; however, in high-density explosives, they believed that immediate, high-order detonation was the usual result even with detonator initiation. In contrast to this, they showed that, in cylindrical charges of coarse grist solid explosives, a stable low-order velocity could be produced. Such a low velocity and also a stable high-order velocity were exhibited by flake TNT at a density of 1.0 g/cm³.

Herzberg and Walker [5,6] appear to have made the most thorough study of corner-turning (the "hook effect"). They found that a delay in lateral spreading of a detonation, initiated over a small area, could occur even when no low-order detonation was present. The delay in lateral spreading extended farther into the acceptor as the strength of the initiator was reduced by interposition of sheets of paper, cardboard, or beaverboard. When low-order detonation was present, lateral spreading began with the transition to high-order detonation. This transition they regarded as occurring first over an area about 4 mm wide and over an axial distance of less than 1 mm. They also observed,

near the initiator, regions of explosive which remained dark and which they termed the "dark space" and the "super dark space." In the super dark space they believed that no high-order detonation occurred.

Held [7] has given descriptions of several interesting experiments in which he attempted to reverse the direction of detonation. He concluded that, within the geometrical constraints imposed, it was very difficult to achieve reversal via corner-turning, and that one may not, as in optics, regard each point on the wavefront as an origin for new wavelets.

Most recently, Jackson et al. [8] have studied the initiation of TATB formulations with flying foils. They found that they could reduce the divergency of the initiated wave by reducing the diameter of the flying foil or its velocity, and observed non-divergent detonation near the limit. Other factors which affected the divergency were the temperature, density, concentration of binder, and particle size.

A positive corner-turning distance is, it seems, exhibited by all explosives, including lead azide [5]. This behavior is more pronounced for liquid and insensitive solid explosives, and can present a severe problem as the initiation limits are approached. To examine this behavior we have devised two forms of corner-turning tests. The first is used primarily as a quality-control test; the second can be used to study details of the process of corner-turning.

II. EXPERIMENTAL

The corner-turning tests have been designed for TATB-based explosives (1, 3, 5-triamino 2, 4, 6-trinitrobenzene). More specifically, the data presented here are for PBX-9502, which is composed of 5% Kel-F and 95% TATB, half of which is reworked TATB. Both the test piece and the booster are of the same material and of the same density ($\pm 0.01 \text{ g/cm}^3$). The density of any booster or acceptor was known to better than 0.002 g/cm^3 .

A. CONTROL TEST

The control test (Fig. 1) is used primarily as a quality-control test to determine if the corner-turning distance for a given batch of explosive is within the required range. It involves a cylindrical test piece initiated by two smaller-diameter cylindrical boosters concentrically glued to each other and then to the test, or acceptor, piece. Cigarette paper acts as the flasher, which is observed with a smear camera equipped with a single slit. Figure 2 shows an example of a film trace obtained with this technique.

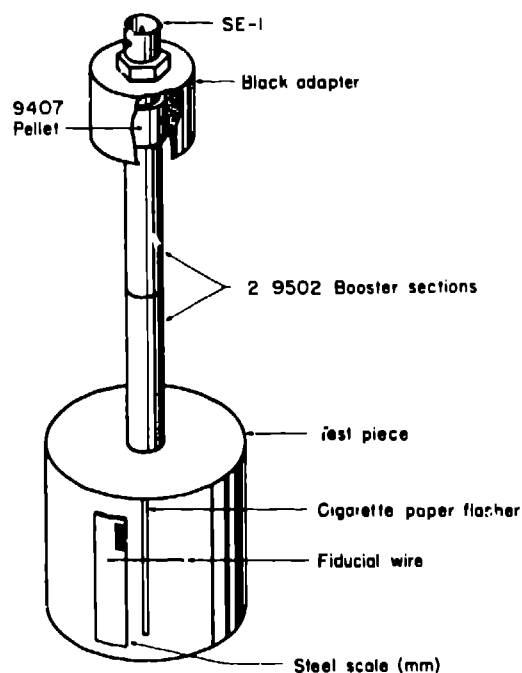


Fig. 1. The control test. One slit is used to observe the breakout trace.

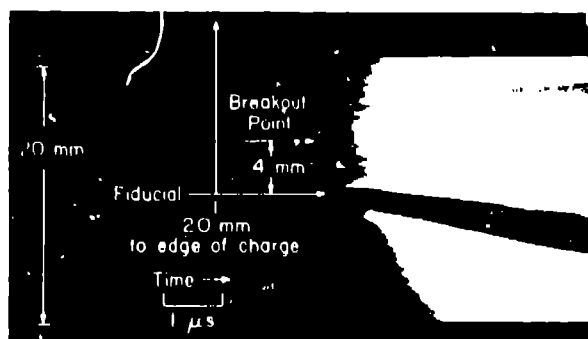


Fig. 2. A film trace using the control design. One trace is observed; the temperature is 25°C . The corner-turning distance or point at which breakout is first measured is about 16 mm from the initiation surface. The fiducial is located 20 mm from the upper surface of the acceptor, where initiation takes place.

B. CORNER-TURNING RESEARCH TEST

The second design, the experimental corner-turning test, used a parallelepiped as the test piece, rather than a cylinder. As with the control test, the acceptor explosive is initiated with two cylindrical boosters. Cigarette paper held with 1/2-inch-thick Plexiglas is used as the flasher, and is placed across a 2- x 2-in. surface of the test piece (the observed surface). A 50-mm-long booster of PBX-9502 is glued to a 1- x 2-in. surface of the test piece. The booster edge is 1 mm from the observed surface, and the booster center is 20 mm from the side edge. These two dimensions have been maintained with all the boosters, which ranged from 7 to 18 mm in diameter. A second identical booster is glued to the first to give a total booster length of 100 mm. The system is initiated in one of two ways; a PBX-9407 pellet 12.7 mm in diam. and 12.7 mm long, and an SE-1 are used for shots with booster diameters of 11 mm or less. For the larger-diameter designs, a PBX-9404 pellet, 1 in. in diameter and 1 in. long is glued to the booster, and this in turn is initiated with the PBX-9407 pellet and an SE-1. By observing the wave traces with 8 slits equally spaced and focused on the front surface of the parallelepiped, we are able to observe the wave pattern from a distance of 1 mm to almost 30 mm, measured laterally from the booster edge (Fig. 3).

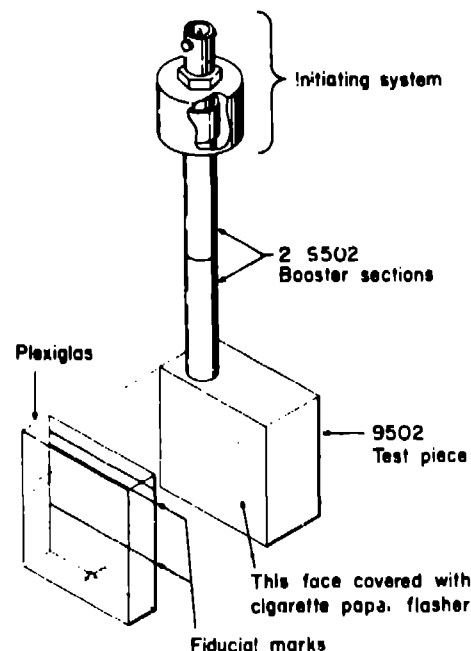


Fig. 3. The research test. Eight equidistant slits are used. The first and last slits are aligned vertically.

An example of a shot record with 8 wave traces is shown in Fig. 4. As with the control test, the film is digitized with respect to time and distance along the observed surface of the test piece. The strength of this design is that several traces may be observed for one shot, and the wave history out to and beyond the corner-turning radius may be determined.

C. CORNER-TURNING MEASUREMENT

The detonation wave is initiated in a donor, or booster column of PBX-9502, preferably not less than six diameters in length. This length permits stabilization of the detonation wave velocity and curvature. Inside the acceptor charge the directionally initiated detonation wave diverges, and a record of its arrival at the acceptor surface is made with a smear camera. If there is a point on a trace that is tangent to the acceptor surface, the record is digitized and fitted about the point of tangency with a cubic or quadratic equation. This equation is then differentiated to find the point of tangency, and the distance of this point below the entrance surface of the test piece is called the "corner-turning distance."

III. EXPERIMENTAL DESIGN

This study consists of the measurement of the corner-turning behavior of PBX-9502 in a matrix of conditions formed with three densities, three temperatures, and four booster

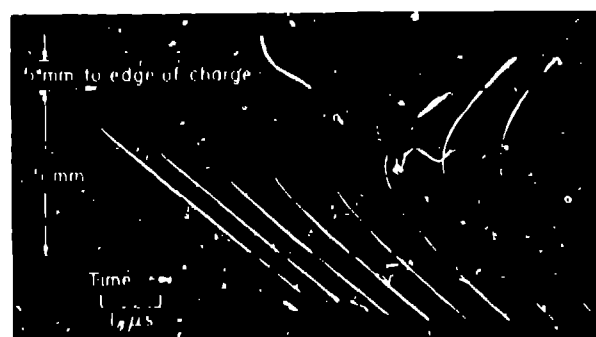


Fig. 4. A film trace in the research test. The diameter of the initiating booster is 10 mm; the density of the test piece is 1.886 g/cm³; the temperature is 25°C. The average corner-turning distance, measured on the last four traces, is 16.7 mm.

diameters. In each test the density of the booster matched that of the acceptor. Four booster diameters were used for each density-temperature pair. For convenience, Table I shows the scaling factors for the booster, relative to the failure diameter of each temperature,

TABLE I
SCALING FACTORS FOR TEMPERATURE DEPENDENT BOOSTER DIAMETERS

Scaling Factors	Booster Diameters (in mm)		
	-55°C	25°C	75°C
<u>Booster Diam</u> <u>Failure Diam</u>	<u>*11.5 mm Failure Diam</u>	<u>*8.5 mm Failure Diam</u>	<u>*6.5 mm Failure Diam</u>
1.04 - 1.08	12.0	9.0	7.0
1.13 - 1.19	13.0	10.0	7.75
1.29 - 1.31	15.0	11.0	8.5
1.53 - 1.57	18.0	13.0	10.0

*Failure diameters were determined at the three reported temperatures for a density of 1.893 g/cm³.

and a density of 1.893 g/cm³. The data are examined from the following viewpoints:

- The variation of the corner-turning distances in a given shot with respect to the radial distance from the booster axis
- The variation of the corner-turning distance with booster diameter, temperature, and density
- The variation of corner-turning radius with density, temperature, and booster diameter
- The volume of the "dead" regions from which no light emanates, where detonation does not occur

IV. CORNER-TURNING DISTANCE DEPENDENCE UPON CORNER-TURNING RADIUS

Using the corner-turning research design, on the average, each shot contained four traces which indicated that corner-turning had occurred. As is shown in Fig. 4, the four slit traces closest to the booster gave no evidence of corner-turning. The corner-turning radius was calculated for the first trace showing corner-turning; this radius is the perpendicular distance from the booster axis to the corresponding slit position on the observed surface (Fig. 5). Experimental values of the corner-turning radius are listed in Table II; the experimental corner-turning distances reported in the same table are the average values of the corner-turning distance for each shot; the range is indicated there as well.

Apparently, the corner-turning radius/distance relationship is that of "go" or "no-go". In order to observe corner-turning, one must use cylindrical test pieces with radii greater than the minimum corner-turning radii, or use the parallelepiped technique.

In several parallelepiped shots the detonation wave did fail to turn the corner;

with these failures one observes the normal pattern of breakout for the first three traces; the remaining slit traces are blank (Fig. 6). Such data show that the divergence of the TATB detonation wave is dependent upon both the corner-turning distance and the radius of the charge. To observe corner-turning and the full divergent wave, both distances must be available. Once the divergence has occurred, that is, beyond the corner-turning radius, the detonation wave stabilized to give essentially the same corner-turning distance for the larger radii.

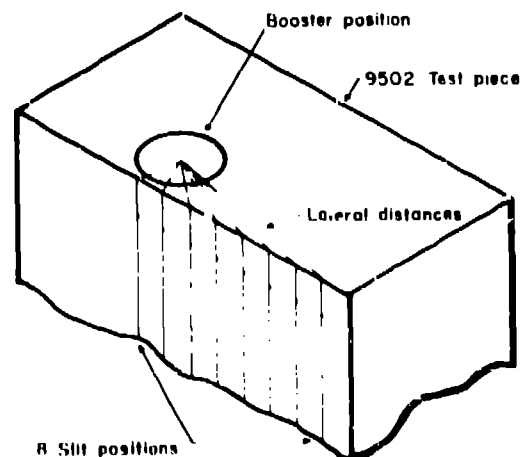


Fig. 5. Lateral distance. With 2.1 magnification, the projected images of the slits are spaced 4 mm at the charge surface. The lateral distances are shown by the lines from the booster center to the edge.

TABLE II
CORNER-TURNING DATA FOR PBX-9502

Shot Number	Density of Test Piece g/cm ³	Diameter of Booster, mm	Corner-Turning Distance, mm (Experimental)	Corner-Turning Distance, mm (Model)	Corner-Turning Radius, mm (Experimental)	Corner-Turning Radius, mm (Model)	"Volume" of Dark Region, mm ³
Temperature = -55° ± 1°C							
F-4866	1.970	12.0	17.94 ± 1.26	14.30	17.46	14.08	5,800
F-4867	1.868	13.0	17.54 ± 1.08	16.21	17.67	14.36	6,400
F-4868	1.870	15.0	15.80 ± 0.93	12.88	18.12	15.96	6,500
F-4869	1.873	18.0	13.84 ± 0.259	11.53	22.36	16.68	4,900
F-4894	1.883	12.0	25.17 ± 1.66	22.04	21.19	18.90	18,300
F-4895	1.887	13.0	26.35 ± 4.29	23.30	21.36	23.52	29,400
F-4876	1.886	15.0	21.74 ± 4.48	20.64	18.12	21.22	19,300
F-4874	1.885	18.0	19.08 ± 1.37	17.30	22.36	19.95	13,800
F-4857	1.900	15.0	Failed, no light beyond 5th slit				
F-4858	1.903	18.0	35.82 (1 point)	35.87	29.73	26.13	51,900
Temperature = 25° ± 1°C							
F-4861	1.874	9.0	15.27 ± 0.49	12.05	13.20	10.95	3,100
F-4865	1.874	10.0	13.06 ± 0.45	10.29	13.42	11.07	2,600
F-4863	1.873	11.0	11.55 ± 0.34	8.65	13.65	11.67	2,300
F-4864	1.869	13.0	10.35 ± 0.22	7.41	14.15	12.12	1,900
F-4881	1.881	9.0	18.67 ± 0.68	16.49	16.92	12.38	5,200
F-4875	1.886	10.0	16.71 ± 0.67	16.74	17.09	12.77	5,200
F-4884	1.886	11.0	15.56 ± 1.18	12.86	13.65	12.81	4,100
F-4886	1.887	13.0	13.02 ± 0.64	11.19	14.15	13.12	3,300
F-4845	1.902	9.0	Failed, no light beyond 3rd slit				
F-4847	1.902	11.0	39.94 ± 2.43	37.83	24.86	21.71	33,400
F-4848	1.900	12.0	29.10 ± 3.79	25.72	25.00	21.55	25,300
F-4840	1.901	13.0	27.74 ± 0.52	23.61	21.36	21.22	22,900
F-4851	1.902	15.0	25.18 ± 0.36	23.16	21.73	21.26	23,100
Temperature = 75° ± 1°C							
F-4872	1.875	7.0	12.54 ± 0.54	13.90	16.62	8.92	2,500
F-4873	1.876	7.75	11.56 ± 0.14	10.15	9.37	9.33	2,000
F-4874	1.877	8.5	11.35 ± 0.46	10.17	13.10	9.46	2,000
F-4892	1.885	7.0	16.57 ± 0.98	13.51	12.82	10.57	3,400
F-4895	1.883	7.75	12.27 ± 0.24	9.20	12.95	9.97	2,000
F-4897	1.883	8.5	11.22 ± 0.56	8.48	13.10	9.26	1,600
F-4898	1.886	10.0	10.73 ± 0.12	7.75	12.09	10.74	1,800
F-4871	1.901	7.0	32.72 ± 1.30	35.44	20.50	13.25	14,500
F-4870	1.900	7.75	34.19 ± 1.06	31.72	20.49	16.37	20,800
F-4894	1.902	8.5	30.24 ± 1.91	30.90	20.68	15.69	17,600
F-4893	1.903	9.0	23.42 ± 0.71	19.10	16.91	14.58	9,800
F-4896	1.904	10.0	28.02 ± 1.98	25.03	24.74	14.13	21,400

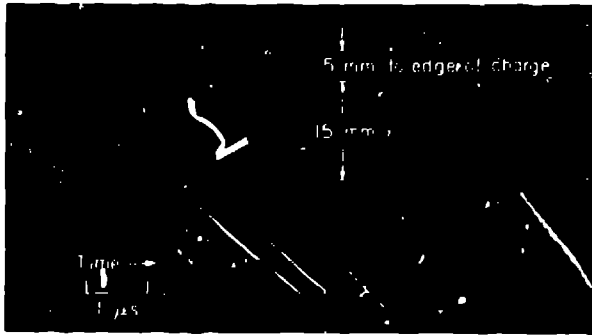


Fig. 6. A failure using the research test. The initiating booster diameter is 9.00 mm; the density of the test piece is 1.902 g/cm³; the temperature is 25°C. Breakout appears in the first three traces, with nothing afterward. The light at the right represents an air shock.

V. CORNER-TURNING DISTANCE-DEPENDENCE ON BOOSTER DIAMETER, DENSITY AND TEMPERATURE

In Fig. 7, the relationship between corner-turning distance and density is plotted for various booster diameters at three temperatures. The data suggest that for a given booster diameter, a density asymptote exists. Such evidence implies that for this density, the detonation wave will fail to turn the corner and will not spread laterally beyond the narrow column corresponding to an axial projection of the initiating booster. The data also suggest that the failure diameter of PBX-9502 increases with density [9].

The booster diameters were chosen to examine the effect of scaling with respect to the failure diameter. There appears to be no strong correlation of the scaled booster diameters with corner-turning distance or radius; rather, the temperature effect is far more significant. The ambient, 11-mm booster, high-density shot was successful, while the corresponding cold, 15-mm booster shot failed. Interestingly, all of the hot shots turned the corner successfully at high density, while only one cold, and two ambient shots detonated at this density.

Thus, as shown in Table II, the corner-turning distance is strongly dependent upon density. A 1% density change may cause a 61% change in the corner turning distance. The temperature effect is also strong; for example, a lowering of the temperature by 130°, from 75°C to -55°C, can cause a 44% increase in the corner-turning distance.

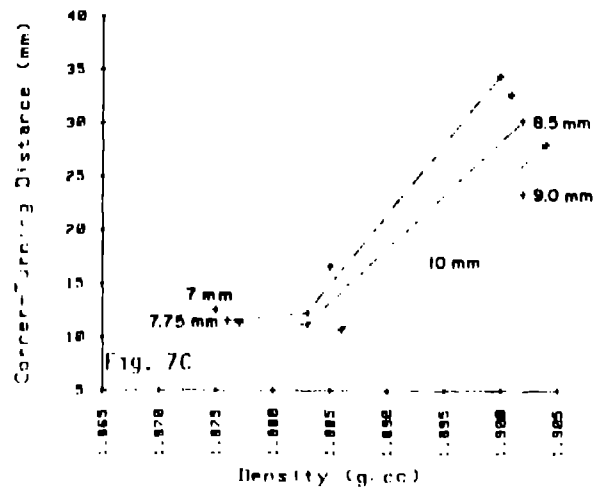
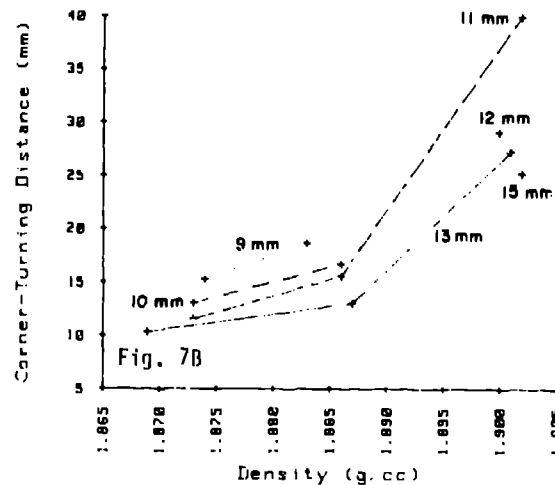
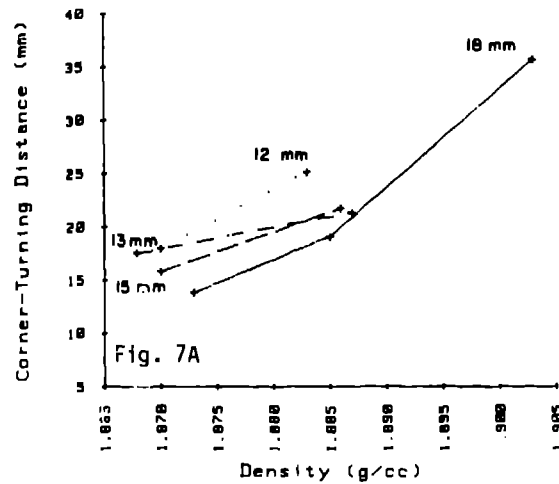


Fig. 7. The average experimental corner-turning distance in relationship to the density of the receptor piece. Figures a, b, and c represent data obtained at -55°C, 25°C, and 75°C, respectively. The booster diameters are indicated in mm on the figures.

VI. CORNER-TURNING RADIUS

The experimental corner-turning radius represents the lateral distance measured from the booster axis to the point at which corner-turning is first observed. In order to calculate the theoretical corner-turning radius, the point of initial break-out for each slit is plotted against the lateral distance from the booster axis (Fig. 8). After fitting these points with a polynomial, the local maximum point is determined. The vertical coordinate of this point is the theoretical corner-turning distance, while the horizontal component is the corner-turning radius (theoretical).

As was observed with the corner-turning distance, the radius is also dependent upon temperature, density, and to a lesser extent, booster diameter. In Fig. 9, the relationship between density and the theoretical corner-turning radius is shown for the three temperatures; in Fig. 10, the closest experimental point at which corner-turning was observed is plotted against density. The first plot permits the estimation of the smallest radius for which corner-turning will be observed; indeed, the theoretical corner-turning radius is generally smaller than that which is observed experimentally. In experimental designs, this radius must be available in order that corner-turning be observed.

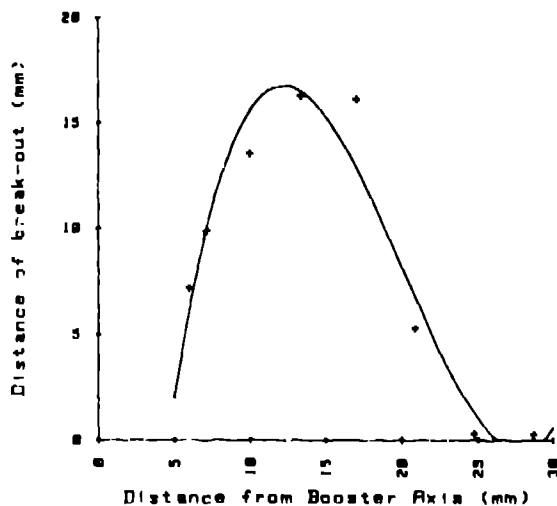


Fig. 8. The closest experimental point for each slit trace to the booster surface of the test piece in relationship to the lateral distance from the booster axis. The solid line represents the third-order polynomial fit used to define the dark region and to determine its volume. These are the data obtained from the traces shown in Fig. 4. A 10-mm booster was used for this shot; the polynomial was then terminated at 5 mm, the corresponding booster edge.

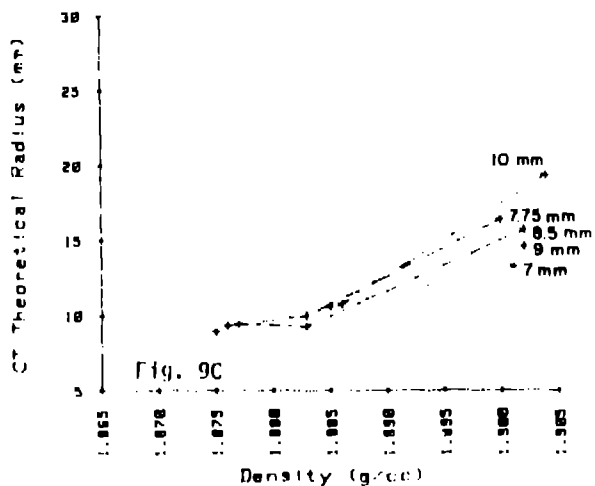
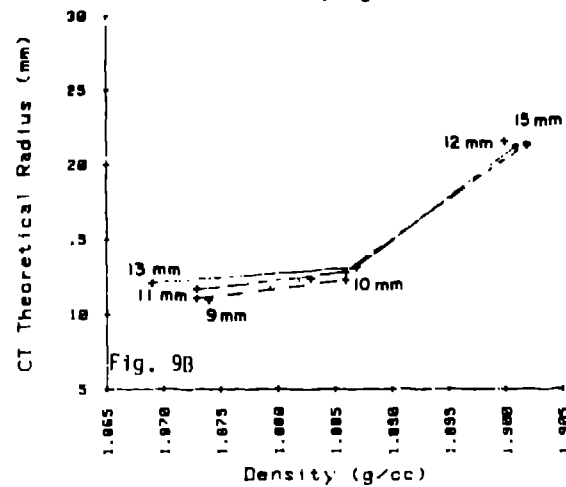
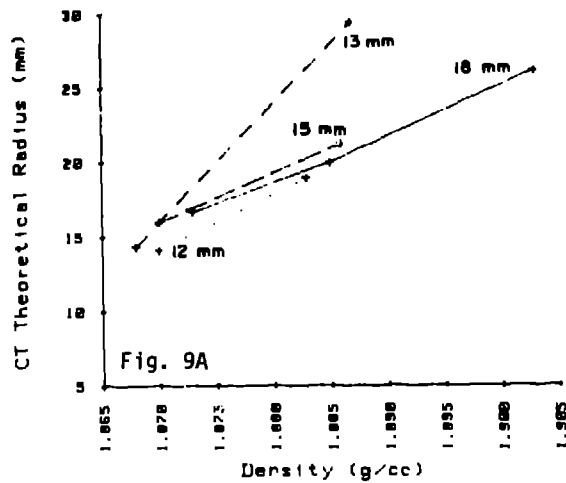


Fig. 9. The theoretical corner-turning radius in relationship to the density of the receptor piece. Figures a, b, and c represent data obtained at -55°C , 25°C , and 75°C , respectively. The booster diameters are indicated in mm on the Figures.

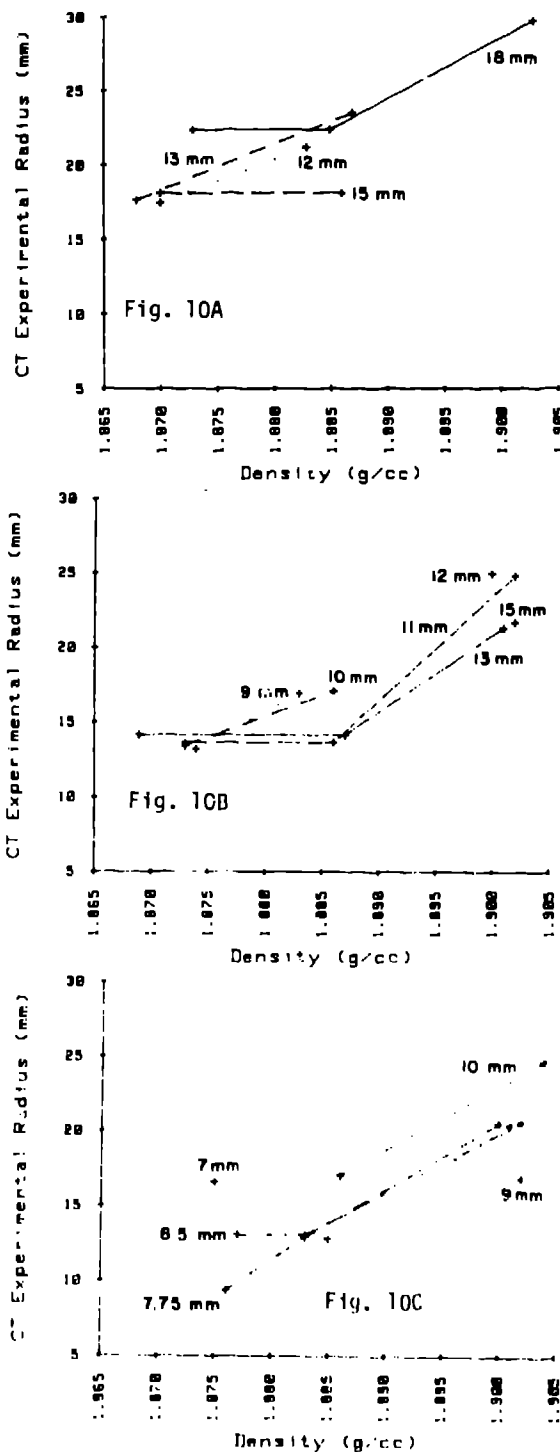


Fig. 10. The experimental corner-turning radius in relationship to the density of the receptor. Figures a, b, and c represent data obtained at -55° , 25° , and 75° , respectively. The booster diameters are indicated in mm on the Figures.

VII. VOLUME OF THE DARK REGION

To determine the dark region, the point nearest the booster surface for each slit trace is plotted against the lateral distance from the booster axis. The region defined by these points and the booster edge of the test piece is the dark region or "undetoned" zone. After fitting these eight points with a cubic polynomial, the volume of undetonated explosive was calculated for each shot. The volumes reported in Table 2 are obtained by rotating the polynomial about the booster axis and integrating from the booster edge to the calculated corner-turning radius. Figure 11 shows the effect of density upon the volume of the dark region. Again it appears that an asymptotic density may be approached as the volume increases sharply.

The dark-region plot is similar to those for corner-turning distance vs density and corner turning radius vs density. In general, one observes density asymptotes that appear to exist within a density range of 1.899 to 1.906 g/cm³ for the hot shots, the two high-scaled ambient tests, and the 18-mm cold shot. For the smaller diameters, failures were observed when using high-density test pieces. We have shown that for a high-scaled booster diameter with medium- to low-density PBX-9502, the results appear to scale under ambient and hot conditions, but not for high density and low temperature.

VIII. CONCLUSIONS

- PBX-9502 exhibits large corner-turning distances and corner-turning radii even with self-boosters well above failure diameter.
- Corner-turning behavior is particularly sensitive to the density of the acceptor, to the diameter of the booster when near the failure diameter, and to variations in the temperature of the acceptor.
- Significant volumes of acceptor explosive in the vicinity of the initiation point are not detonated, and much of this volume is probably unreacted.
- The failure diameter of PBX-9502 probably increases with density.

Acknowledgements

We would like to acknowledge the careful work of many individuals in making high quality explosives available, especially H. L. Flaugh and H. L. Keller of WX-3, and M. C. Clancy of WX-2. We also recognize the competent efforts of A. A. Gallegos, C. M. Montoya, R. P. Archuleta, and C. E. Busse, who provided the necessary consistency in the field work. For technical photographic support, we are obligated to B. E. Langley and W. C. Chiles. We thank J. R. Travis and J. B. Ramsay for helpful discussions.

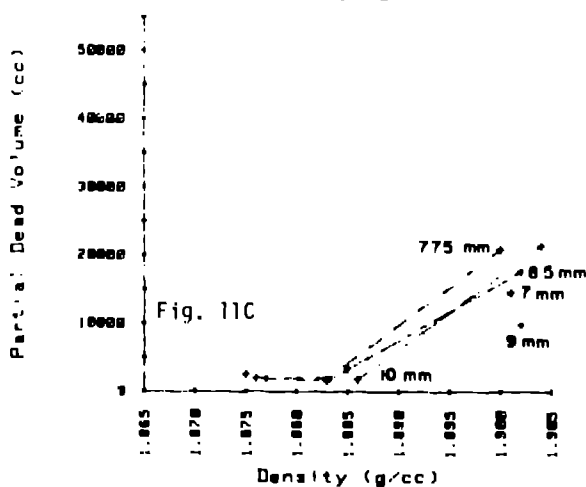
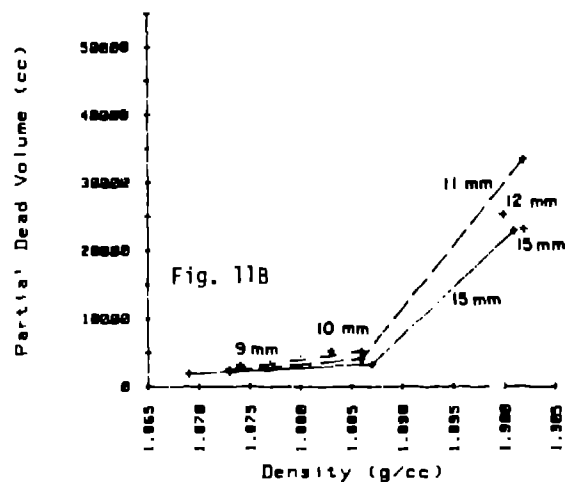
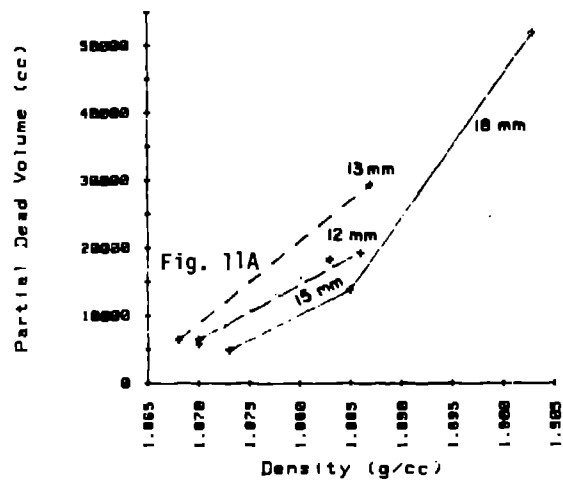


Fig. 11. The partial volume of undetonated explosive in relationship to the density of the receptive piece. Figures a, b, and c represent data obtained at -55°C , 25°C , and 75°C respectively. The booster diameters are indicated in mm on the Figures.

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